The MODIS Aerosol Algorithm, Products, and Validation

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard both NASA's *Terra* and *Aqua* satellites is making near-global daily observations of the earth in a wide spectral range (0.41–15 μm). These measurements are used to derive spectral aerosol optical thickness and aerosol size parameters over both land and ocean. The aerosol products available over land include aerosol optical thickness at three visible wavelengths, a measure of the fraction of aerosol optical thickness attributed to the fine mode, and several derived parameters including reflected spectral solar flux at the top of the atmosphere. Over the ocean, the aerosol optical thickness is provided in seven wavelengths from 0.47 to 2.13 μm. In addition, quantitative aerosol size information includes effective radius of the aerosol and quantitative fraction of optical thickness attributed to the fine mode. Spectral irradiance contributed by the aerosol, mass concentration, and number of cloud condensation nuclei round out the list of available aerosol products over the ocean. The spectral optical thickness and effective radius of the aerosol over the ocean are validated by comparison with two years of Aerosol Robotic Network (AERONET) data gleaned from 132 AERONET stations. Eight thousand MODIS aerosol retrievals collocated with AERONET measurements confirm that one standard deviation of MODIS optical thickness retrievals fall within the predicted uncertainty of $\Delta\tau = \pm0.03 \pm0.05\tau$ over ocean and $\Delta\tau = \pm0.05 \pm 0.15\tau$ over land. Two hundred and seventy-one MODIS aerosol retrievals collocated with AERONET inversions at island and coastal sites suggest that one standard deviation of MODIS effective radius retrievals falls within $\Delta r_{\mathrm{eff}} = \pm0.11$ μm. The accuracy of the MODIS retrievals suggests that the product can be used to help narrow the uncertainties associated with aerosol radiative forcing of global climate.

1. Introduction

The Chesapeake Lighthouse and Aircraft Measurements for Satellites (CLAMS) field experiment was designed to aid the development and evaluation of satellite algorithms that retrieve geophysical parameters important to the earth's radiative balance and estimates of global change. Aerosols are one of those important geophysical parameters that determine the earth's energy balance and hydrological cycle. These suspended airborne particles scatter solar radiation back, absorb solar radiation in the atmosphere, and shade the earth's surface. Airborne particles act as cloud condensation nuclei entering into cloud processes and thereby change cloud reflectivity and the hydrological cycle (Twomey 1977; Rosenfield and Lensky 1998). Aerosols also affect human health and reduce visibility (Samet et al. 2000). Some aerosol types are natural, such as wind-blown desert dust or sea salt caused by breaking waves. Other aerosol types are created from human activities such as urban/industrial pollution and biomass burning. Unlike CO_2, another atmospheric pollutant input into the atmosphere from human activity, aerosols are not well mixed in the atmosphere and, because of their spatial and temporal variability, the uncertainty of estimating human-induced aerosol forcing on climate and the hydrological cycle is on the order of 2 W m^{-2}, which is equal to the estimated forcing of all the greenhouse

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gases combined (Houghton et al. 2001). Therefore, characterizing global aerosol distribution presents one of our major challenges today (Kaufman et al. 2002).

Operational remote sensing of aerosols from long-term satellites provides a means to achieve a global and seasonal characterization of aerosol. Satellite sensors view the entire earth and produce global images, thus resolving the spatial patterns resulting from the spatial inhomogeneities of aerosol sources. Daily global images from polar-orbiting satellites (Husar et al. 1997; Herman et al. 1997; Torres et al. 2002) and more frequent imagery from geostationary satellites (Prins et al. 1998) resolve the temporal patterns resulting from the short lifetimes of aerosols, which are on the order of a few days to a week.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a new sensor with the ability to characterize the spatial and temporal characteristics of the global aerosol field. Launched aboard NASA's *Terra* and *Aqua* satellites in December 1999 and May 2002, MODIS has 36 channels spanning the spectral range from 0.41 to 15 μm representing three spatial resolutions: 250 m (2 channels), 500 m (5 channels), and 1 km (29 channels). The aerosol retrieval makes use of seven of these channels (0.47–2.13 μm) to retrieve aerosol characteristics and uses additional wavelengths in other parts of the spectrum to identify clouds and river sediments (Ackerman et al. 1998; Gao et al. 2002; Martins et al. 2002; Li et al. 2003). Unlike previous satellite sensors, which did not have sufficient spectral diversity, MODIS has the unique ability to retrieve aerosol optical thickness with greater accuracy and to retrieve parameters characterizing aerosol size (Tanré et al. 1996; Tanré et al. 1997). The results section of this paper shows that MODIS's ability to separate aerosols by size can be used as a proxy for separating human-generated aerosol from natural sources, which aids substantially in estimating global human-induced aerosol forcing (Kaufman et al. 2002).

The first MODIS instrument was launched aboard *Terra* at the end of 1999 and began transmitting data at the end of February 2000. Algorithms were in place, designed to use the observed radiances to derive many important aerosol products. Early comparisons of the retrieved aerosol parameters with ground-based validation data showed remarkable agreement between the two types of data (Chu et al. 2002; Remer et al. 2002), but also showed us situations in which the algorithms could be improved. Almost immediately, the algorithms were modified to reflect a better understanding of the instrument's capabilities and the nature of aerosols and clouds. In a companion study in this special issue, the MODIS aerosol algorithm over ocean is compared with an independent aerosol retrieval algorithm applied to the same dataset of MODIS radiances (Ignatov et al. 2005). In another companion paper in this special issue, the MODIS retrievals over land and ocean are evaluated regionally for the specific time and location of the CLAMS field study using the additional resources available during the CLAMS intensive observing period (Levy et al. 2005). However, in the present study we take a global view. We give a comprehensive description of the MODIS aerosol algorithms, highlighting the changes that were implemented postlaunch. We describe the wealth of aerosol products derived from MODIS data and available to any user. Last, we show some of the global comparisons to ground-based data as validation for the products previously described.

6. Conclusions

Characterizing the global aerosol system is essential to understanding the earth's climate system and estimating potential global climate change. The MODIS instrument flying aboard NASA's *Terra* and *Aqua* satellites provides a look at the aerosol system over both land and ocean on a daily basis. The derivation of aerosol products from the MODIS-measured radiances relies on the broad spectrum that MODIS measures, ranging from the visible into the mid-infrared, and the 500-m spatial resolution, which allows for better cloud identification and clearing than was possible with previous instruments. The mature MODIS algorithm includes aerosol optical thickness at several wavelengths, information on particle size, and aerosol-reflected flux at the top of the atmosphere, which is expected to be more accurate than the optical thickness retrievals. An extensive validation effort that collocated over 8000 MODIS retrievals with AERONET measurements of optical thickness show that globally, the MODIS products are accurate to within prelaunch expectations, namely, $\pm 0.05 \pm 0.15\tau$ over land and $\pm 0.03 \pm 0.05\tau$ over ocean. In particular, the retrieval of aerosol over oceans consistently shows remarkably good agreement with virtually no offset or bias through the range of optical thickness where most observations occur. Regional analysis, however, shows specific issues for certain locations. Comparison of MODIS and AERONET monthly means at eight specific locations scattered globally demonstrates that the MODIS retrievals are not affected by cloud contamination at those sites, and that MODIS long-term statistics agree with AERONET to within 0.10 over land and to within 0.035 at oceanic island sites. MODIS-derived aerosol size parameters are in general agreement with the same quantities derived by AERONET instruments on the ground. For moderate optical thickness, one standard deviation of MODIS effective radius retrievals falls within ± 0.11 μm of AERONET measurements. Comparison of MODIS and AERONET monthly mean values of η, the ratio of fine-mode aerosol optical thickness to total optical thickness at eight specific sites suggests that over-ocean MODIS values agree to within 20%, which exceeds the prelaunch estimate of $\pm 30\%$ for individual retrievals. However, at low aerosol optical thickness ($\tau < 0.15$) the MODIS size retrievals are susceptible to small aberrations in the calibration and other factors, which introduce greater uncertainty. In addition, dust, with its nonspherical shapes, introduce uncertainty in both the optical thickness and size parameter retrievals. This latter issue will be addressed with the incorporation of nonspherical phase functions into the next version of the algorithms. In the meantime, the MODIS aerosol products are sufficiently accurate for a variety of applications, including improved estimates of observationally based aerosol radiative effects.